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OPTIMIZING TAPERED MICROFIBER SENSOR DESIGN AND SIMULATION

S. Al-Askari[1], B. A. Hamida[1], S. Khan[1] and S. W. Harun [2]
[1]Department of Electrical and Computer Engineering, International Islamic University Malaysia,
Jalan Gombak, Kuala Lumpur, Selangor, Malaysia
[2]Photonics Research Centre, University of Malaya, Kuala Lumpur, Malaysia
E-Mail: belal@iium.edu.my

ABSTRACT

Refractive index sensors measure the evanescent field energy to sense various environmental parameters. Evanescent field-based sensors depend on the tapered area geometry which is one of the important factors for optimising the sensor performance as well as achieving better sensitivity and higher resolution. Tapering fabrication process needs to be controlled properly in order to achieve the optimal design. A two-dimensional model of the tapered sensor is proposed and simulated using Finite Element Analysis software, COMSOL Multiphysics. The light scattering phenomenon is visualized for taper and waist areas. The effects of the taper length, the waist length and the waist diameter have been explored in order to find the optimal geometries design. The model provides initial data to the designer to program and control the taper ration and the taper length the fabrication process in order to obtain the highest penetration depth at the highest resolution. The results show that the evanescent field is significantly high when the core diameter is close or below the wavelength. The output graph illustrates that when the tapering ratio decreases, more light propagate into the surrounding making the sensor more sensitive to the ambient changes. The simulation shows that the profile of the sensor can be fine-tuned by changing the tapering ratio of the waist and the length of the taper in order to obtain high performance, ultra-high-resolution evanescent field sensor.

Keywords: microfiber, tapered fiber, refractive index, RI, evanescent field, FEA, COMSOL.

INTRODUCTION

Recently, optical devices are being increasingly used for chemical and biochemical sensing applications and accordingly have been attracting greater research consideration due to their exceptional advantages over electrical transducers, such as their low cost, compact size, low noise, high sensitivity and immunity to electromagnetic [1]. Optical microfiber sensor can be defined as an optical (or photonic) micro-wire that has a waist diameter close to, or even below, the wavelength of the guided light. It has generally a high contrast between its core's RI (Refractive Index) and the surrounding's RI. Due to this contrast, and due to its small dimension, it has a large fraction of the guided field of light, making it highly sensitive to the surrounding ambient changes [2, 3].

Tapered sensors are utilized especially for environment monitoring systems by measuring various environmental parameters such as displacement, temperature, strain, gas, humidity and pressure [4]. Taper fiber is usually fabricated by heating the regular-sized fiber and drawing it, as shown in Figure-1, where an optical fiber with an initial diameter (D_O) is heated and stretched to produce a microfiber with a diameter of (D_L).

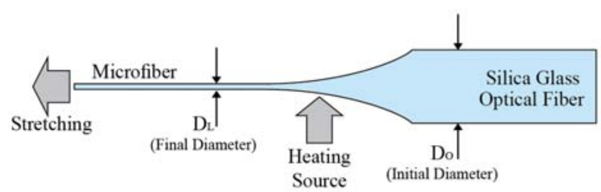

Figure-1. Simplified microfiber fabrication technique.

Refractive index sensing is widely employed due to the fact that many biological and chemical specimens can be identified by measuring their refractive indices. The working principle of the refractive index sensor is that the refractive index of the external environment (which acts as a cladding) can be sensed by the optical transmission attenuation which is produced by the interaction between the evanescent wave and the external environment. An optical source is used to emit the light into a microfiber exposed to the ambient. The transmission medium is ended by a photodetector or Optical Spectrum Analyzer (OSA) to determine the transmission attenuation, and consequently, the refractive index of the surrounding.

A theoretical model for tapered optical fiber sensor is proposed in [5]. The highest sensitivity and the best performance for the proposed sensor geometry are explored for different taper ratios (TR) apart from other important factors. However, the evanescent field intensity (energy per unit area) relies on the RI of both fiber core as well as the core radius and the guided light wavelength

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(λ). Ahmad et al. calculated in [6] the penetration depth of the evanescent field of a refractive index sensor based on a ray-tracing model (shown in Figure-2). The effects of different tapering ratios, different lengths, and light launching angles are explored in order to obtain the highest penetration depth. The higher the penetration depth is, the more sensitive the sensor is. Obtaining penetration depths close to the cell size is a concern in bio-sensing applications in order to design high resolution sensor. The penetration depth is generally expressed as following:

$$d_P = \frac{\lambda}{2\pi(n_1^2 \sin^2\theta - n_2^2)^{1/2}} \tag{1}$$

Where λ is the wavelength, n_1 is the core RI (refractive index), n_2 is the cladding RI, and θ is the light incident angle. However, the penetration depth of a linear taper is expressed in [6] as a function of NA (numerical aperture), RI of the core, RI of the surrounding medium, L (taper length), TR (taper ratio R_L/R_O), α_O (initial launch angle) and z (taper position). These parameters can be fine-tuned to enhance the penetration depth.

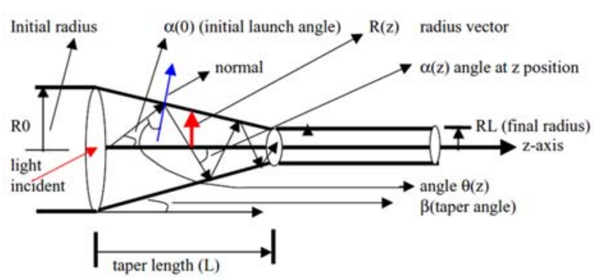

Figure-2. Ray-tracing model [6].

The characteristics of two microfiber FEA models are studied comparatively in [7]. Energy difference between the two ports of the model is measured to determine the loss due to evanescent field. The study focused on the response of the sensor for different surrounding mediums by changing the refractive index of the medium and monitoring the light propagation in the surroundings.

In this paper, The influence of different microfiber structures on the energy of the evanescent calculated using 2D FEA model in order to optimize the structure design and to find the best (Taper Ratio, Taper Length) combination.

FABRICATION

There are several methods to fabricate the tapered microfiber sensor. One of the commonly used tapering techniques is flame brushing technique. It has many merits, such like, high flexibility in flame movement, controllable length of stretched fiber and high speed. Microfiber can be fabricated using this technique in accurate dimensions with good reproducibility. Flame brushing enables the fabrication of bi-conical tapered fibers which defined as microfiber that has both ends connected to a single-mode fiber (SMF). The bi-conical tapered fibers scheme is used widely in fabricating low-loss microfiber sensors and devices.

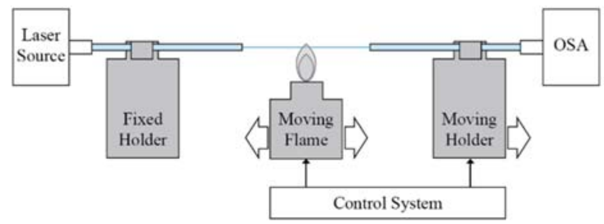

Figure-3. Flame brushing technique.

Figure-3 illustrates the schematic of the flame brushing technique where the coating of several centimetres of the SMF is removed prior to the fabrication process of the microfiber. Then, a translation stage is used to place and hold the SMF horizontally by two fiber holders. During stretching, the torch moves along the distance of the uncoated segment and heats it. This movement provides a good uniformity along the heat region. To monitor the transmission spectrum during the fabrication, a light source is injected into one end, while the other end is connected to the OSA [8]. To achieve a specific waist diameter, the initial uncoated length and the final taper length should be selected precisely. By controlling the taper length, drawing speed and the flame speed during the fabrication process, optimal design with the highest amount of light propagated to the surroundings, and consequently, the highest sensitivity, can be obtained.

SIMULATION

COMSOL Multiphysics 5.1 is used to simulate this model. We define five regions in the model as shown in Figure 4(a). The upper and the bottom regions have a fixed height of L_O and a regular-sized fiber diameter D_O. These two regions represent the coated parts of the fiber which are out of our interest. The middle region (usually called the sensing region) has a waist diameter of (TR x D_O), where TR ≤ 1. The height of it is defined as (n x L), where L is the taper length and n is a parameter that is used to study different lengths effect.

The material of the five regions is defined as SMF-28, which is a commercial fiber operating at 1310/1550 nm wavelength. The numerical aperture of SMF-28 is 0.13 and its core diameter is 9.3±0.5 µm.

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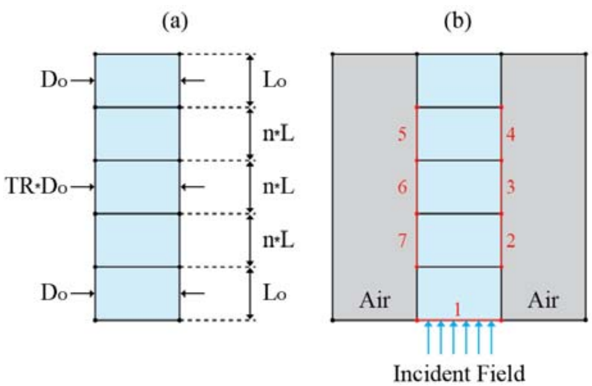

Figure-4. Proposed model.

As shown in Figure-4(b), the model is surrounded by air with refractive index =1. The incident field is directed perpendicularly to the boundary 1. The average energy per area unit of the boundaries 2, 3, 4, 5, 6 and 7 was derived to estimate the strength of the evanescent field. A parametric sweep study on TR and n is used to figure out the evanescent field for different taper ratios and lengths. TR range was defined as 0.1-1 by a step of 0.1 whereas n range was defined as 1-10 by a step of 0.5. Figure-5 illustrates some examples of the impact of TR and n on the model geometry.

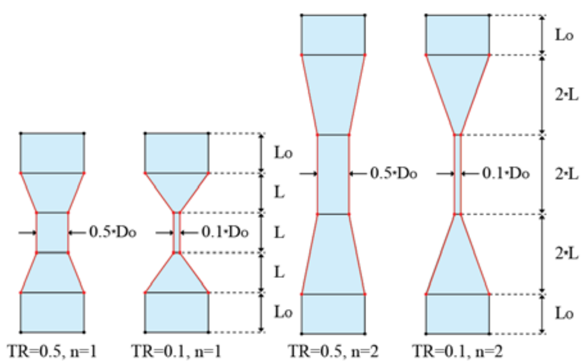

Figure-5. The proposed model for:
(TR, n) = (0.5, 1), (0.1, 1), (0.5, 2), and (0.1, 2).

RESULTS AND DISCUSSIONS

The frequency of the incident electric field was set to (c/λ) where c is the speed of light in vacuum and λ is 1550 nm. The results showed that the light propagated basically along the fiber. This is a logical result since the silica refractive index is higher than the air RI. However, there was a proportion of the light propagated into the surrounding medium. Visual graphs were produced for all proposed TR and n values. Figure 6 illustrates the light propagation for n=5 and TR= 0.2, 0.4, 0.6, and 0.8.

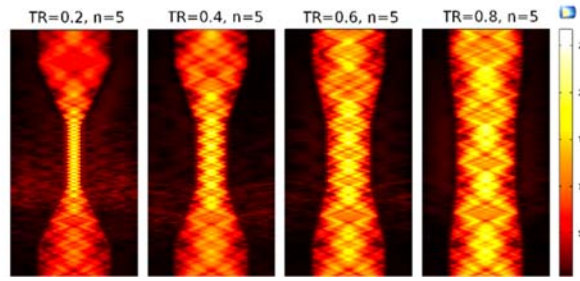

Figure-6. The electric field propagating for n=5, and TR=0.2, 0.4, 0.6, and 0.8.

It can be seen that when TR decreased, more light propagated into the surrounding. This is because of the decrease in the effective index of the microfiber in the waist area. Moreover, the power of the evanescent field depends on (λ /r). [3] Thus, larger evanescent field is obtained from smaller taper radii for a specific wavelength. Large evanescent field is required in sensing applications where the propagated light interacts with the surrounding.

The length of the taper is also playing an important role in changing the strength of the evanescent field. The length of the taper determines how much refraction along the microfiber will occur. To figure out its impact, results for TR= 0.1, 0.3, 0.5, 0.7, and 09 for all values of n are listed in Table 1. Entire results are also represented in a line chart in Figure-7.

Table-1. The evanescent field (V/m) for different (TR, n).

TR=	0.1	0.3	0.5	0.7	0.9
n=1	9.459	4.664	2.656	1.986	1.761
n=1.5	7.566	4.369	2.683	2.103	1.647
n=2	8.107	3.601	2.822	2.05	1.735
n=2.5	7.779	3.796	2.708	2.066	1.591
n=3	7.33	3.81	2.757	2.099	1.662
n=3.5	7.294	4.177	2.767	2.107	1.695
n=4	8.107	4.073	2.704	2.026	1.674
n=4.5	7.654	3.874	2.585	2.07	1.612
n=5	8.023	3.889	2.566	2.067	1.918
n=5.5	7.188	3.728	2.654	2.086	1.63
n=6	7.574	3.889	2.483	2.059	1.666
n=6.5	7.369	4.151	2.836	2.039	1.613
n=7	7.598	3.935	2.804	2.109	1.616
n=7.5	7.547	3.714	2.512	2.075	1.713
n=8	7.572	3.66	2.654	2.181	1.636
n=8.5	7.621	3.745	2.608	2.027	1.737
n=9	7.227	3.831	2.625	2.041	1.663
n=9.5	7.927	3.775	2.597	2.109	1.718
n=10	7.782	3.89	2.583	2.041	1.692

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From Figure-7, it is obvious that the evanescent field is significantly high for TR=0.1 comparing to all other taper ratios. When TR=0.1, the diameter of the sensing region will decrease to be lower than the wavelength (930 nm < 1550 nm). However, TR=0.1 is hard to be achieved practically because the tapering process is complex and difficult to be controlled accurately. In addition, the sensors are fragile, especially, when the diameter is extremely small. Figure-7 shows also the best (TR,n) combinations that enhance the performance of the sensor and increase its resolution. For example, for TR=0.2, we can see that the highest evanescent field can be achieved at n=2.5 and 4. The influence of different microfiber structure on the energy of the evanescent can be calculated easily using this model in order to optimize the structure design and to find the best (TR, n) combination.

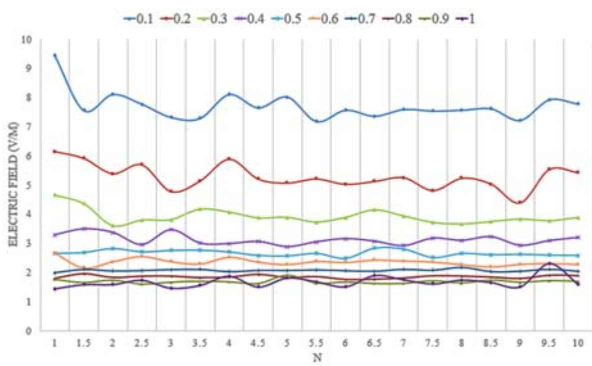

Figure-7. The evanescent field (V/m) for different (TR, n) combinations.

CONCLUSIONS

A two-dimensional model of the tapered sensor is proposed and simulated using Finite Element Analysis software, COMSOL Multiphysics. The light scattering phenomenon is visualized for taper and waist areas. The effects of the taper length, the waist length and the waist diameter have been explored in order to find the optimal geometries design. By studying the influence of the taper ratio and the taper lengths, we are able to fine-tune our sensor design to suit our application before starting the fabrication process. The results provide initial data to the designer to program and control the taper length, drawing speed, and the flame speed during the fabrication process in order to obtain the ideal design with the highest resolution. Generally, the evanescent field energy is inversely proportional to the taper ratio. The results show that the evanescent field is significantly high when the core diameter is close to or lower than the wavelength. Group of optimal (TR, n) combinations were found and represented as the peaks of the line graph. These findings can make up an important basis for photonic engineers to design high resolution tapered sensors for different applications.

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